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Technical Letter
No. 1110-2-365

31 August 1994

Engineering and Design

NONLINEAR, INCREMENTAL STRUCTURAL ANALYSIS OF MASSIVE CONCRETE STRUCTURES

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NONLINEAR, INCREMENTAL STRUCTURAL ANALYSIS OF MASSIVE CONCRETE STRUCTURES

1. Purpose

This engineer technical letter (ETL) provides guidance for performing a nonlinear, incremental structural analysis (NISA) for massive concrete structures (MCS).

2. Applicability

This ETL applies to HQUSACE elements, major subordinate commands, districts, laboratories, and field operating activities (FOA) having responsibilities for the design of civil works projects.

3. References

a. EM 1110-2-2000, Standard Practice for Concrete.

b. ACI Committee 207. 1973 (Reapproved 1986). "Effect of Restraint, Volume Change, and Reinforcement on Cracking of Massive Concrete," ACI 207.2R-73, American Concrete Institute, Box 19150, Detroit, MI 48219.

c. ANATECH Research Corp. 1992. "ANACAP-U, ANATECH Concrete Analysis Package, Version 92-2.2, User's Manual," P. O. Box 9165, Ladolla, CA 92038.

d. Garner, S. B., Bombich, A. A., Norman, C. D., Merrill, C., Fehl, B., and Jones, H. W. 1992. "Nonlinear, Incremental Structural Analysis of Olmsted Locks and Dams - Volume I, Main Text," Technical Report SL-92-28, U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

e. Hibbitt, Karlsson, and Sorenson, Inc. 1989. "ABAQUS User's Manual, Version 4.9," Pawtucket, RI 02860.

4. Discussion

a. Background. Current design practice for MCS was developed in the 1960's. Structural analysis methods did not integrate the effects of thermal and mechanical stresses and did not accurately predict the behavior of complex hydraulic structures. Results were usually safe, but very conservative. Advances in analysis techniques and computer technology have greatly improved structural design capabilities. Finite element analysis can be used to account for complex geometry and loading, thermal stresses, nonlinear material behavior, and sequential construction. These techniques have already been applied to the design of lock monoliths, arch dams, and other MCS. They provide a more realistic, comprehensive understanding of structural behavior.

b. Types of massive concrete structures. MCS are defined by the American Concrete Institute Committee 207 (1973-R86) as "any large volume of cast-in-place concrete with dimensions large enough to require that measures be taken to cope with the generation of heat and attendant volume changes to minimize cracking." There are three types of MCS commonly used for civil works projects. Gravity structures are used for dams and lock walls; thick shell structures are used for arch dams; and thick

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reinforced plates are used for U-frame locks, large pump stations, and powerhouses.

5. Criteria

a. Design guidance. NISA should be used as a supplemental tool for the design of MCS. The MCS must also satisfy applicable criteria contained in other guidance documents. When a NISA is needed to achieve any of the listed objectives presented in paragraph 5*b*, it should be performed per the guidance in Appendix A. This guidance has been developed from design experience on several recent civil works projects. Examples of such designs are provided by Garner, et al. (1992). Excerpts from this reference are included in Appendix B.

b. Objectives. NISA of MCS should be used when it is necessary and cost effective to achieve one or more of the following design objectives.

(1) To develop structures with *improved performance* where existing similar structures have exhibited extensive cracking during construction or operation. This objective is to limit cracking to minor occurrences in noncritical areas. It is neither necessary nor realistic to completely eliminate cracking.

(2) To more accurately *predict behavior of unprecedented structures* for which limited experience is available; for example, those with unusual structural configuration, extreme loadings, unusual construction constraints, or severe operational requirements.

(3) To provide *cost savings* by revising the structural configuration, material requirements, or construction parameters.

c. Action.

(1) The need to perform a NISA should be identified during the Feasibility Phase of project development. Necessary design studies and resources should be included in the Project Management Plan. Proper identification of objectives is the key to determining the required scope of studies. Contact CECW-ED for assistance in determining appropriate levels of investigation and the necessary resources.

(2) Structural engineers should perform a NISA during the early stages of design. This will enable the design team to use NISA results to make key design decisions at appropriate times. Usually the analysis will occur during the initial stages of preconstruction engineering and design (PED). However, if an unprecedented structural configuration is being proposed, it may be necessary to perform a NISA during the feasibility phase to identify requirements for design changes and unusual construction procedures which will significantly affect project costs. Guidance for performing a NISA during the feasibility phase is contained in Annex 1 of Appendix A.

(3) A NISA should be based on test results of the proposed concrete mixture for the project. Therefore, when a NISA is expected, it is critical to conduct concrete materials tests at the earliest possible time. The structural engineer must communicate this requirement to the materials engineer, since normal thermal studies required by EM 1110-2-2000 may be conducted later in the design process. If test results are delayed excessively, it may be necessary to initiate the NISA without the test data. If this undesirable situation occurs, properties should be selected as described in Annex 1, Appendix A, for a NISA during the feasibility phase. Once testing is completed, the performance of the NISA during the feasibility phase must be verified with NISA's using the material properties from the test results.

(4) The structural engineer is primarily responsible for performing the NISA. However, adequate analysis and evaluation of design alternatives require participation of a design team including structural, materials, geotechnical, cost, and construction engineers. This team must ensure that NISA results are properly incorporated into the overall design of the MCS. Proper coordination is required for: selection of concrete properties, foundation properties, and construction parameters; refinement of the analysis through changes in structural configuration or construction parameters, or revised material data for concrete or foundation; economic evaluation of design alternatives.

(5) Due to the fact that NISA is a state-of-the-art procedure and there are many complex issues associated with performing a NISA, periodic review meetings should be held throughout the performance of a NISA study to ensure that the plan of action

being pursued is acceptable to all elements involved. Representatives from CECW-ED and CECW-EG and their counterparts from the division office reviewing the project documents should be present at these meetings.

(6) Actual construction conditions may not match the assumed conditions used for the NISA. When this occurs, the team should evaluate the altered conditions and determine the need to revise the design or conduct additional NISA studies.

d. Documentation. Results of the NISA should be documented in a separate design memorandum entitled "Nonlinear, Incremental Structural Analysis." Required report content is identified in Appendix A.

e. Deviations. Any deviation from specific requirements of the enclosed guidance requires consultation with and the approval of CECW-ED. Such approval should be obtained in advance of the analysis. Approval is required for actions such as deletion of required parameter combinations, use of narrow bandwidths without material property tests, or use of a computer code other than ABAQUS (Hibbitt, Karlsson, and Sorenson 1989) with the ANACAP-U subroutine (ANATECH Research Corp. 1992).

FOR THE DIRECTOR OF CIVIL WORKS:

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2 Appendices
APP A - Nonlinear, Incremental Structural Analysis (NISA) of Massive Concrete Structures
APP B - Examples